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Surface Electrical Stimulation to Realize Task Oriented Hand Motion

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Abstract— **This paper describes a new surface electrical stimulation approach to the production of task-oriented functional hand and finger movements in people with upper extremity paralysis as the result of brain or spinal cord injury. The approach involves the need to first identify ("map") the distribution of the optimal electrical stimulation sites. Multi-channel electrical surface stimulation is then applied to obtain the desired motions. We describe here the grasping of a paper cup by the hand and three-digit pinching induced by this approach in a healthy subject as well as the results of a training trial in two adults with C6-level spinal cord injury.**

I. Introduction

It is often impossible for people who have suffered a central nervous system injury such as a stroke or spinal cord injury to use their limbs effectively despite the presence of an intact peripheral nervous system. A number of approaches have been developed to ameliorate this situation.

FES (functional electrical stimulation) is one of these methods [1] and uses electrical stimulation of nerves and muscles to restore functional of a paralyzed limb. A number of researchers have explored its applicability for the upper extremities. Handa et al., for example, investigated stimulation patterns most effective in the upper extremities and have reported the restoration of function of a paralyzed arm by means of an implanted electrode. [2]-[5]. Watanabe et al. used proportional-integral-derivative (PID) method to control wrist joint motion by FES [6]. Although Ring et al. [7] and Snoek et al. [8], on the other hand, have designed a neuroprosthetic FES device for the hand, called a "NESS Handmaster," that uses surface electrical stimulation (SES), there have been few studies that focus on the use of SES to induce skilled movements of the fingers and hands.

The ultimate goal of our research is to restore lost hand functionality with the use of SES FES. This paper describes our preliminary efforts: 1) the identification ("mapping") of the forearm and thenar muscles, 2) the induction of motion of individual fingers by means of surface electrical stimulation, 3) the reproduction of the motions of grasping a paper cup and three-digit pinch common to many daily activities, and 4) the application of mapping and the therapeutic electrical stimulation (TES) in two patients with spinal cord injury.

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II. Mapping

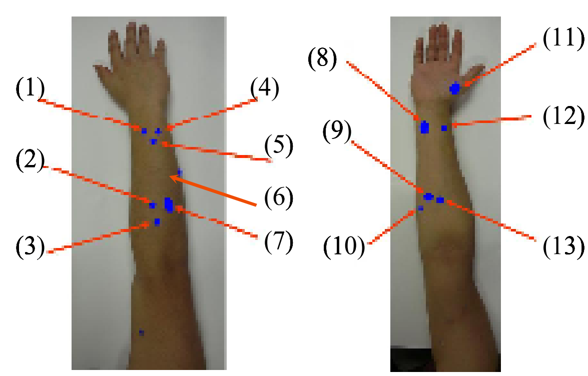
A controlled current stimulation device (Neu Tracer NT-11, Top Company, Japan) was used to identify optimal muscle SES sites. One healthy man (aged 24 years) participated in this portion of the study. The mapping procedure was as follows.

Step 1) Identification of the motor points of individual muscles.

Step 2) Raising of the current intensity of the device, we investigate around the points found in Step 1) to clarify SES area while observing the muscle's stimulated contractions.

Step 3) Establishing the maximum tolerable level of stimulation for each muscle.

Figure 1 shows the distribution of the motor points, as detected in Step 1). The *flexor digitorum superficialis* (FDS), *flexor digitorum profundus* (FDP), thenar muscles (TM), *flexor pollicis longus* (FPL), *extensor carpi radialis longus* (ECRL), *extensor carpi radialis brevis* (ECRB), *extensor digitorum* (ED), *extensor pollicis longus* (EPL), *extensor pollicis brevis* (EPB), *pronator teres*, *pronator quadratus* and *extensor indius* were specified.



(1) EPB (5) *Extensor indius* (8) *Pronator quandratus* (11) TM
(2) ECRB (6) FDP (9) FDS (12) FPL
(3) ECRL (7) ED (10) FCU (13) FCR
(4) EPL

Fig. 1 Mapping of hand and forearm

The *flexor digitorum superficialis* (FDS), due to its complex role in the motion of the fingers, was investigated particularly thoroughly with attention directed to the areas responsible for isolated movements of the 1) the index and 2) the ring fingers as well as the simultaneous movements of the 3) the middle and ring fingers, and 4) the little and ring fingers respectively (Fig. 2).

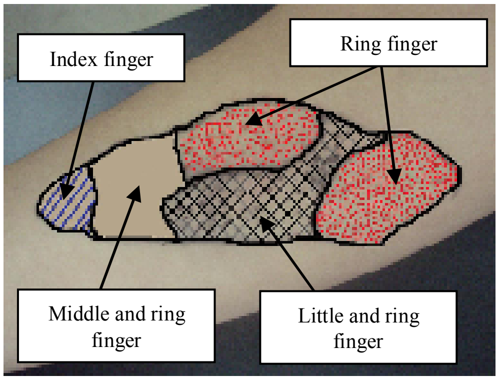
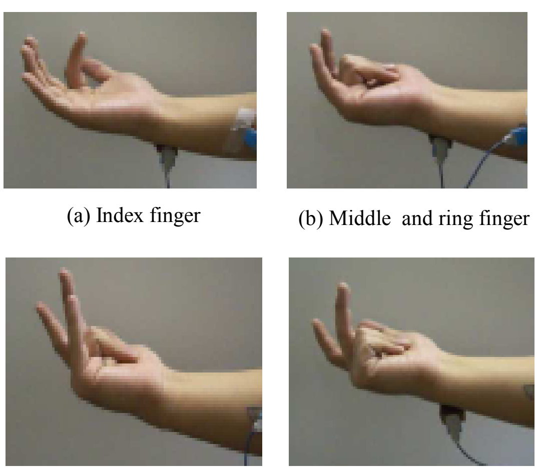


Fig. 2 Detailed mapping of FDS

III. MOTION OF INDIVIDUAL FINGERS

The subject was asked to relax and we stimulated the FDS using the stimulation sites identified in the mapping procedures outlined above (Fig. 2) to confirm that SES could effectively induce flexion of the middle and ring fingers in isolation as well as that of the little and ring fingers simultaneously (Fig. 3). We confirmed that SES might be effective in the production of task-oriented motions.



(a) Index finger (b) Middle and ring finger

(c) Ring finger (d) Little and ring finger

Fig. 3 Individual motions

IV. GRASPING AND RELEASE OF A PAPER CUP

Next, we examined the grasping a weighted (200 gm) paper cup. A multi-channel electrical stimulation approach was utilized. Electrodes were attached to the FDS and FDP, TM, FPL for grasping, and ECRL and extensor ECRB, ED, EPL, EPB and *extensor indius* for the extension of the fingers and release at the locations identified in our mapping exercise. Muscles were placed into three groups and stimulated in sequence.

First, extension of fingers and the hand was induced by electrical stimulation. Second, fingers and wrist were stimulated to flex and grasp the cup. The third step involved release of the cup following the stimulated extension of the hand and fingers (Fig.4).

The SES pulsing waveform utilized a carrier frequency of 5,000 Hz and a stimulation frequency of 40 Hz (Fig. 5). The voltage, V_{pp}, was adjusted as shown in Fig. 6 to permit successful completion of the grasping task. Trial and error was used to refine movement. Ch1 (channel 1) was used to apply SES to the ECRB and ECRL, ED, EPB, EPL, and *extensor indius*, Ch2 for the FDS and FDP, and Ch3 for the TM and FPL. Muscles of a single group received the same stimulating voltage. When the paper cup was grasped, Ch1 was also stimulated to fix the angle of the wrist and to prevent over flexion of the wrist. It was noted that the muscles were sensitive to small differences in stimulation intensities and that careful voltage control will be required to obtain stable and effective movements.

Fig. 4 Grasping of the paper cup

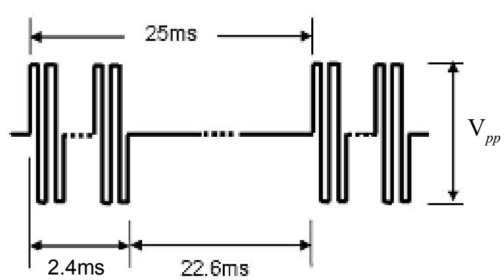


Fig. 5 Waveform of the stimulation

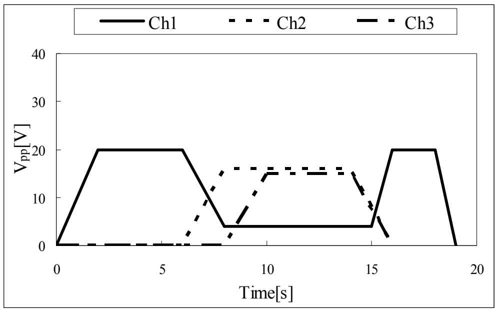


Fig. 6 Voltage of the stimulation

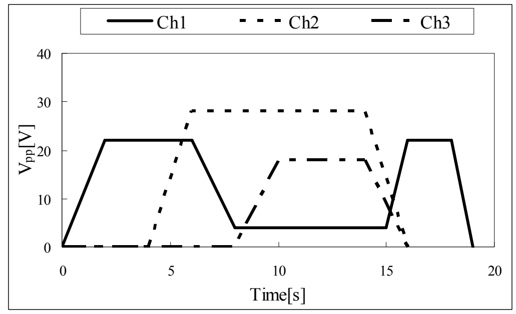
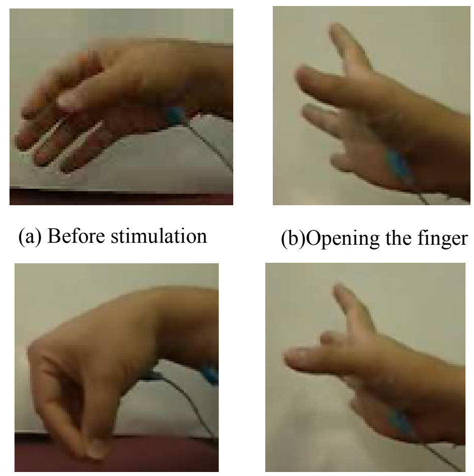


Fig. 7 Voltage of the stimulation



(a) Before stimulation (b)Opening the finger s

(c)Three digit pinching (d)Opening the fingers

Fig. 8 Dexterous motion

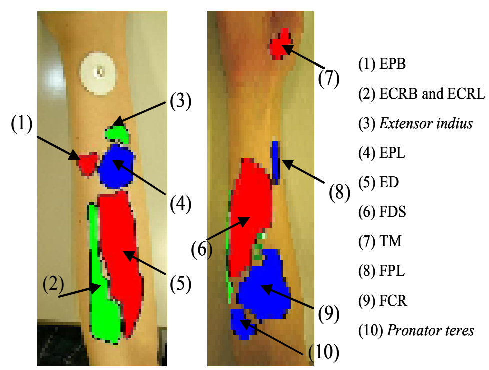


Fig. 9 Mapping (female subject)

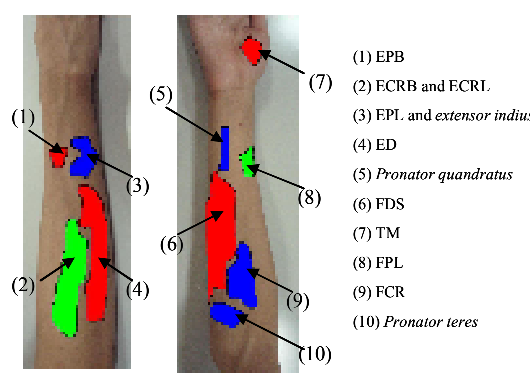


Fig. 10 Mapping (male subject)

V. THREE-DIGIT PINCHING AND RELEASE

Finally, we reproduced the series of motions involved in the performance of a three digit pinch (i.e., the thumb and first two fingers) and release such as may be involved in the turning of a key. The subject was a healthy young man who had been asked to relax and not assist the motions. Five steps were required:

Step 1) Opening the hand.
Step 2) Flexing the thumb.
Step 3) Pronation of the forearm.
Step 4) Three-digit pinching.
Step 5) Opening the hand again.

The waveform shown in Fig. 5 was used to stimulate the muscles. The stimulation voltage, V_{pp} was varied as illustrated in Fig. 7.

Electrodes were attached to the ECRB and ECRL, ED, EPB, EPL, *extensor indius*, FDS, FDP, TM, and *pronator quadratus*. In Fig. 7, Ch1 provided stimulation to the ECRB and ECRL, ED, EPB, EPL, and *extensor indius*, Ch2 to the FDS and FDP, and Ch3 to the TM and *pronator quadratus*. Figure 8 shows the motion induced by the stimulation. The results suggest that complex functional motions can be effectively induced by multi-channel SES.

VI. APPLICATION TO SPINAL CORD INJURY PATIENTS

A. *Mapping*

Two subjects (1 male and 1 female, 5 and 6 years after injure, respectively) with stable C6-level spinal cord injury participated in this portion of the study. Muscle mapping was performed in a manner outlined above for the neurologically intact subject with (due to their sensory deficits) the maximum values of stimulation current determined by their physician. The distribution of the muscles of the subjects with spinal cord injury (with a few exceptions such as the *pronator quadratus* of the female subject) could be specified as well (Fig. 9 and 10).

B. Therapeutic Electrical Stimulation

Starting in November 2008, TES of the extensors in the forearms of the two SCI patients, as specified by mapping, was carried out for 20 minutes 2-3 times a week (total 12 weeks) with the goal of increasing muscular strength and decreasing spasticity and contractures of the joints. The detailed map of the extensors was divided into 2 areas: 2 electrodes were attached to cover the areas (1) and (3) (including (4) in the case of the female subject), and the areas (2) and (5), as shown in Fig. 9 and 10. The stimulation sequence was determined by trial and error and the findings in healthy men.

At the beginning of the TES, the fingers did not extend fully as in voluntary motion in either subject. Figure 11 shows the hand of the female patient during stimulation.

Two months later, the female subject, who, unlike her male counterpart, had partial active motion of the fingers at the beginning of the trial, was able to fully extend all the fingers when the muscles were stimulated (Fig. 12). After three months of TES, the female subject was given TES on the flexor side.

After three months of TES, the male subject still had spasticity in the middle and ring fingers when the muscles were stimulated. Therefore, the TES of the extensors was extended for an additional month. But, these fingers couldn't fully extend after an additional month. After four months of TES, treatment was shifted to the flexor musculature.

Both subjects' stimulation voltages decreased after the TES. The capacity for voluntary motion had not changed in either patient after four months. Subject forearms have undergone sequential MRI imaging and quantitative tracking of their movement trajectories with a 3-SPACE (Polhemus Inc., USA) apparatus. This data is currently undergoing analysis.

VII. CONCLUSION

The motion of individual fingers, the grasping of a paper cup and 3-digitpinch motions common to everyday life can be induced by task-oriented multi-channel electrical stimulation of mapped areas of the forearm. And we applied TES to the two spinal cord injured persons. These results are promising but additional quantitative information about optimal stimulation parameters and the effects of SES on muscle structure and movement (such as the MRI and 3-SPACE data currently undergoing assessment) is necessary before practical use of SES, mapping technique for TES can be applied in its most effective manner in the clinical situation.

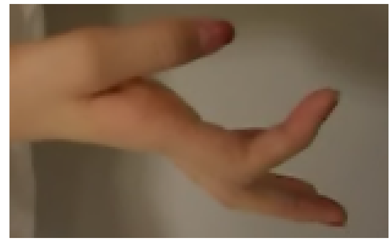


Fig. 11 Stimulated finger (beginning of TES)

Fig. 12 Stimulated finger (after two months)

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